



HHS Public Access

Author manuscript

Min Eng. Author manuscript; available in PMC 2016 August 12.

Published in final edited form as:

Min Eng. 2016 August ; 68(8): 50–58.

Comparison of MERV 16 and HEPA filters for cab filtration of underground mining equipment

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Abstract

Significant strides have been made in optimizing the design of filtration and pressurization systems used on the enclosed cabs of mobile mining equipment to reduce respirable dust and provide the best air quality to the equipment operators. Considering all of the advances made in this area, one aspect that still needed to be evaluated was a comparison of the efficiencies of the different filters used in these systems. As high-efficiency particulate arrestance (HEPA) filters provide the highest filtering efficiency, the general assumption would be that they would also provide the greatest level of protection to workers. Researchers for the U.S. National Institute for Occupational Safety and Health (NIOSH) speculated, based upon a previous laboratory study, that filters with minimum efficiency reporting value, or MERV rating, of 16 may be a more appropriate choice than HEPA filters in most cases for the mining industry. A study was therefore performed comparing HEPA and MERV 16 filters on two kinds of underground limestone mining equipment, a roof bolter and a face drill, to evaluate this theory. Testing showed that, at the 95-percent confidence level, there was no statistical difference between the efficiencies of the two types of filters on the two kinds of mining equipment. As the MERV 16 filters were less restrictive, provided greater airflow and cab pressurization, cost less and required less-frequent replacement than the HEPA filters, the MERV 16 filters were concluded to be the optimal choice for both the roof bolter and the face drill in this comparative-analysis case study. Another key finding of this study is the substantial improvement in the effectiveness of filtration and pressurization systems when using a final filter design.

Introduction

When most health and safety professionals think today about filtration efficiencies and their correlation with protecting workers' health, the normal assumption is the higher the efficiency of a filter, the greater the protection afforded to the workers. The next logical step is to believe that filters meeting the high-efficiency particulate arrestance (HEPA) standard deliver the greatest protection for workers because they provide the highest filtering efficiency. Obviously, high-efficiency intake filters are a necessity for an effective cab filtration and pressurization system on mobile mining equipment, but what is the optimal

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filter efficiency for achieving high levels of cab protection factor (PF) performance over the service life of filters? To address this question, an in-depth U.S. National Institute for Occupational Safety and Health (NIOSH) laboratory research study was performed over several years with numerous simultaneous field studies to retrofit enclosed cabs in use on mobile mining equipment with newer and more effective filtration and pressurization systems.

Table 1 summarizes the minimum efficiency reporting values, commonly known as MERV ratings, and filtration efficiencies corresponding to three size ranges of dust/contaminant particles, obtained from the *American Society of Heating, Refrigerating and Air-Conditioning Engineers Handbook* (ASHRAE, 2012), with the HEPA efficiency added at the bottom for comparison. A MERV rating is a value designated by ASHRAE to compare the effectiveness of different air filters, while HEPA is the most common filtration term known today, recognized by most nonhealth and safety professionals.

To be rated as HEPA quality, filters must meet specifications set by the U.S. Department of Energy and must be capable of filtering at least 99.97 percent of particles sized 0.3 μm and larger, and Table 1 shows a considerable jump in filtration efficiency for 0.3- μm particles and larger from 95 percent for MERV 16 filters to 99.97 percent for HEPA filters. Along with their wide recognition comes the assumption that HEPA filters should be used in nearly all applications. However, these filters are more costly and restrictive than MERV 16 filters, placing additional demands on the overall filtering system, including the intake fan. The increased restriction and pressure drop across HEPA filters result in decreased intake airflow and lower positive pressure within the cab, both of which are detrimental to the overall system performance. This situation also raises the likelihood of leakage around the filter if the design and construction of the filter housing has minor imperfections.

When dealing with mobile equipment used in the mining and construction industries, because of the constant movement, vibration and stress placed on the enclosed cab over years of use, the likelihood of stress cracks and leakage points in the heating, ventilating and air conditioning (HVAC) and filtration system becomes more of an issue. Based upon the results of a previous NIOSH laboratory study analyzing diesel particulate matter, we hypothesized that a MERV 16 intake filter using a mechanical filter media would be the optimal design for the majority of enclosed cabs for mining applications, rather than a HEPA filter (Cecala et al., 2016; Cecala et al., 2014; Noll, Cecala and Organiscak, 2011, 2014).

When the research to improve air quality in the enclosed cabs of mobile equipment was started about 15 years ago, NIOSH's Pittsburgh Mining Research Division conducted the analysis by performing gravimetric sampling and using light-scattering nephelometers to obtain instantaneous measurements inside and outside of the enclosed cabs during in-mine testing. This sampling process was time consuming, as well as complicated, because it included the time periods when the equipment operator was entering and exiting the cab, which allowed dust and contaminants to enter (Cecala et al., 2007; Heitbrink et al., 2000).

In recent years, particle counters have advanced in many ways, becoming more economical and simple to use, and these instruments have improved the accuracy of the testing in this

research. The current study was performed using particle counters during nonproduction time periods while the roof bolter and face drill were located outside the mine. We believe these static conditions provide much more reliable results and the most favorable and comparable PF values for each enclosed cab. We also believe that this study is the first of its kind, attempting to compare HEPA and MERV 16 filters in the same enclosed cabs of mining machinery used in the industry.

Testing

A comparative evaluation was performed of the air quality in the enclosed cabs of a roof bolter and a face drill (J.H. Fletcher & Co., Huntington, WV) using MERV 16 and HEPA filters. Identical test protocols were implemented for each test series to achieve, as close as is practical, identical tests over the study period. Figure 1 shows the filtration and pressurization unit on the face drill along with a plan view of the system design, which was identical on the roof bolter. Each filtration and pressurization unit used a RESPA-CF Vortex HyperFLOW intake air filtration pressurizer unit (Sy-Klone International, Jacksonville, FL) and a final panel filter (J.H. Fletcher & Co., Huntington, WV) inside the HVAC component, through which all the intake and recirculation air flowed before entering the cab. The intake air filter pressurizer contained a cyclonic precleaner that used a centrifugal design to expel dust particles sized greater than 5.0 μm and prevent them from depositing on the filter, thus minimizing dust loading and extending filter life. Standard size RESPA-CF filter cartridges, 15.24 cm (6 in.) in diameter and 20.32 cm (8 in.) high, were used throughout the study. The J.H. Fletcher & Co. final panel filter, with width of 28.91 cm (11.38 in.), height of 44.45 cm (17.5 in.) and thickness of 9.53 cm (3.75 in.), was mounted at the exhaust discharge of the HVAC system. All cab testing was conducted with the pressurizer unit operating and the HVAC system fan on the high flowrate setting. A matrix evaluation of several filter system configurations was also performed as a secondary study component, as well as a comparison of new versus used filters.

The study was conducted at the new Shelly Materials underground limestone mine near Zanesville, OH. At the end of the daylight shift, the equipment operators would bring their equipment outside the mine to service. When servicing was completed, the operators would park the roof bolter or face drill outside the mine and turn it over to us to perform our testing. At no time in the study did the operators and mine personnel clean or replace any filters associated with this testing. The two most important measurements of the NIOSH test protocol were particle count, to determine a PF value for the filtration and pressurization system's effectiveness for each of the enclosed cabs, and airflow, to determine intake and recirculation air volumes during each test that were compared over time as the filters loaded with dust. Engine hours were also recorded each month during testing to provide a relative measure of equipment use and dust loading on the filters over time. At the beginning of the testing, we installed a pressure monitoring device and datalogger in the enclosed cab of the face drill and that of the roof bolter to determine and record the positive cab pressure created by the filtration and pressurization system, aimed at documenting how the positive pressure decreased over time as the filters loaded with dust and created additional filter differential pressure, which would cause the airflow to decrease. The datalogger was attached to the pressure monitor and could record one-minute pressure averages for 28 days. We returned

within the 28 days to download the positive pressure data and conduct particle count and airflow measurements.

Testing was performed in a static mode, meaning the equipment was running without anyone in the enclosed cab to stir up or create any in-cab dust sources. This provided the highest possible PF for each of the enclosed cabs. From May through November of 2013, roughly on a monthly basis, testing was performed using MERV 16 intake and final filters. The testing was then repeated from May through November of 2014 using HEPA intake and final filters.

Particle count measurements

Two ARTI/Met One HHPC-6 particle counters (Hach Ultra Analytics, Grants Pass, OR) were used to simultaneously sample and record the inside and outside cab particle size concentrations for one-minute periods over a 30-minute test (NIOSH, 2008; Organiscak and Cecala, 2008; Organiscak, Cecala and Noll, 2013). These instruments count airborne particles in six size channels from 0.3 to greater than 5.0 μm . The test medium was airborne particles present in the ambient air surrounding the unoccupied stationary cab enclosure with the filtration system operating on the high fan setting. The inside and outside cab instruments were then alternated for another 30-minute test to average out any instrument sampling biases for each test. The last 15 minutes of data from each test were used to calculate the average outside and inside cab concentrations during the lowest steady-state particle count conditions. The PFs were determined from the cumulative submicrometer (0.3–1.0 μm) particle concentrations because most of the ambient air particles resided in this size range (NIOSH, 2008; Organiscak, Cecala and Noll, 2013). A PF for each test replicate was determined by dividing the average outside particle concentration by the average inside particle concentration. The calculated PF for the cab was the average of these two test replicates. The 95 percent confidence levels of the PFs were determined by calculating the propagation of standard error estimates (for a two-variable ratio) during each test replicate and pooling these standard errors using Satterthwaite's standard error approximation (Organiscak, Cecala and Noll, 2013). Because of the comparative nature of this study, any effects from extraneous factors from testing at a mine site are believed to be minimal. The PF represents a reduction ratio of all the exterior and interior particles removed by dividing the outside concentration by the inside concentration and is the same calculation used when determining the effectiveness of personal protective equipment such as respirators.

Airflow and cab pressure measurements

Airflow readings were taken for the intake and recirculation circuits of the cab enclosures' filtration system for various filter combinations. During the field study, a VelociCALC 8346 hotwire anemometer (TSI Inc., Shoreview, MN) was used to measure the centerline air velocity in the middle of a 76.2-cm (30-in.)-long section of a smooth PVC pipe with diameter of 6.10 cm (2.4 in.) that was added to the outlet of the intake filtering unit. For the recirculation component, one-minute moving traverse velocity measurements were taken with a vane anemometer (Davis Instruments, Vernon Hills, IL) over the recirculation filter

inlet area. A more detailed description of these measurements can be found in Cecala, Organiscak and Noll (2012).

The cabs' inside-to-outside differential static pressures were also measured to ensure that cab pressurization was achieved. During the MERV 16 filter testing in 2013, the KT-CABPRES-EL1-ENG electronic pressure monitor system 0.0–200 Pa (0.8-in. water gauge) (Sy-Klone International, Jacksonville, FL) was used. During the HEPA filter testing in 2014, the DM-2003-LCD differential pressure transmitter 0.0–125 Pa (0.500-in. water gauge) (Dwyer Instruments, Inc., Michigan City, IN) was used. Both of these static pressure monitors had electronic outputs. The pressure data were downloaded to a HOBO U12-006 datalogger (Onset Computer Corp., Pocasset, MA) and stored on the datalogger as one-minute pressure averages for up to a 28-day period.

Results

Figure 2 shows the PFs determined for the enclosed cabs of the face drill and roof bolter, as well as the intake airflows with the MERV 16 filters and the HEPA filters. The PF values, plotted on a log-normal scale, show significant improvements in air quality achieved with both types of filters for both the face drill and the roof bolter. There are three missing data points: the first two for the face drill and the roof bolter in October 2013 due to a several-week federal government shutdown that started on Oct. 1, and the third for the test on Aug. 27, 2014, in which the face drill was not operational.

The PFs for the face drill ranged from 612 to 6,337 for the MERV 16 filters and 685 to 8,133 for the HEPA filters. This compares with PFs for the roof bolter of 77 to 1,021 for the MERV 16 filters and 182 to 1,425 for the HEPA filters. Based upon these ranges, the assumption would be that the HEPA filters provided higher PFs than the MERV 16 filters, but when all the values were averaged over the entire test period, this was not the case, as shown in Fig. 3. For the face drill, the average PF was 3,898 with the MERV 16 filters, slightly higher than the average PF of 3,677 with the HEPA filters. For the roof bolter, the average PF was 573 with the MERV 16 filters, slightly lower than the average PF of 681 with the HEPA filters. Statistically, at the 95 percent confidence level, there is no difference between the PF values for either the face drill or the roof bolter between the two types of filters. This conclusion is based on insignificant differences found between the filter types when using a two-tailed parametric t-test, assuming unequal variances, and a nonparametric Wilcoxon test. The 95 percent confidence levels for the cab PFs are also shown in Fig. 3 and illustrate no significant differences between the filters used on each cab. There is, however, a significant difference in the PF values when comparing the enclosed cabs on the face drill with the roof bolter, which will be discussed in the following section.

The first point to note in the results is the extremely high Comparison of the average PF values for the face drill and roof bolter with the MERV 16 filters and the HEPA filters. PF values for both the face drill and the roof bolter, especially the face drill, indicating the tremendous improvement in air quality in the enclosed cabs. These PF values are the highest recorded in any of NIOSH's field testing to date, and it is believed that the static test conditions and the use of a final filter were the two significant contributing factors. In

Organiscak, Cecala and Noll (2014), it was stated that any filtration and pressurization design that directs all the intake and recirculation airflow through a final filter significantly increases the system's effectiveness, which was the case for the J.H. Fletcher design in both the roof bolter and face drill (Fig. 2).

Another interesting point to note is that for the MERV 16 filters, when the PF values for new filter conditions in May 2013 are compared with the values for the following two readings in June and July, the results show the intake and final filters loading with dust and becoming more efficient. For the face drill, the PF was 612 with new filters, increasing to 4,106 for June and 6,337 for July. Similarly, for the roof bolter, the PF was 300 with new filters, increasing to 790 for June and 1,021 for July. Averaging the PF values for June and July, when the filters were loaded with dust, shows the substantial increase in filtering efficiency for both the face drill and the roof bolter, with improvement factors of 8.5 and 3.0 times the original, or clean filter, values, respectively.

This was not the case when considering the results of the HEPA filter testing, performed in 2014. At the start of the test, there were new intake and final filters in both the face and the roof bolter. The intake filters loaded with dust as testing progressed, and once the intake airflow dropped below the $0.71\text{-m}^3/\text{min}$ level (25 cfm), a new intake filter was installed in the system. For the HEPA testing, there were five instances when new intake filters were used: three for the face drill and two for the roof bolter. In only one of these five instances was there a significant PF increase for the same two-month post-analysis used for the MERV 16 comparison. This occurred for the first HEPA filter test on the roof bolter, when there was a 3.2-times increase in the PF when the average of the two post-month values was compared with the PF value with all new filters. For the three instances of new intake filters on the face drill, there was one case of a very slight improvement of 1.1 times the original PF value.

The last point to highlight is the changes in intake airflow values shown in Fig. 2. In Cecala et al. (2014), it was stated that in order to provide a sufficient quantity of intake air to ensure the equipment operator does not become asphyxiated from being in an enclosed area, a minimum quantity of at least $0.71\text{ m}^3/\text{min}$ (25 cfm) is recommended to dilute the carbon dioxide exhaled by the operator (American Society of Agricultural and Biological Engineers, 2013). Based upon this value, it was determined during this study that whenever the intake airflow of either the face drill or the roof bolter reached or dropped below the $0.71\text{-m}^3/\text{min}$ (25-cfm) level, a new intake filter would be installed. When this occurred, after taking the particle count and airflow measurements with the old filter, the new intake filter was installed, and the particle count and airflow measurements were repeated. For the testing of the MERV 16 filters, there were no intake filter changes necessary, although a new filter would have been needed on the face drill if the test had continued past November. For the HEPA filters, new intake filters were necessary on two occasions for the face drill on July 29 and Sept. 24, and on one occasion for the roof bolter on July 29. By comparing the declines in intake airflows for the MERV 16 filters with those for the HEPA filters on the face drill and on the roof bolter, it is seen how quickly the HEPA filters were loaded with dust and diesel particles, and needed to be replaced. This is also apparent in Fig. 4, which plots the cab pressures and intake airflows for the face drill with the MERV 16 filters and with the HEPA filters. The figure shows the starting points for the intake airflows and the cab

pressures for both filter types, and then how the values declined as both the intake and final filters loaded with dust. Figure 4 underscores the superior operating life cycle of the MERV 16 filters compared with the HEPA filters, with higher cab pressure throughout the life cycle, as well as how an in-cab pressure monitor can be used to indicate the need for filter changes. Recirculation airflows for both cabs were between 4.08 and 7.0 m³/min (144 and 247 cfm) for the MERV 16 final filter and between 3.82 and 5.86 m³/min (135 and 207 cfm) for the HEPA final filter with the HVAC on the highest fan setting during the study.

Discussion

Although this study showed no long-term significant difference in a cab's PFs when using the MERV 16 filters and the HEPA filters, it did show a significant difference between the roof bolter's and the face drill's PFs when using identical filters. This difference is speculated to be the result of sealing or integrity deviations between the mechanical structures of the two identical HVAC/filtration systems. Additional evidence to this effect was observed early in the testing of the MERV 16 filters on the roof bolter, when particle count measurements were taken with several extra filter combinations, after 257 hours of operation, to examine the mathematical modeling of these system changes (Organiscak, Cecala and Noll, 2014). The filter combinations tested included adding a used recirculation filter to the system and removing the final filter from the system. Figure 5 shows the results of these tests as well as the test when the intake and final MERV 16 filters were new. This figure also shows the modeled PFs developed in Organiscak, Cecala and Noll (2014) under these test configurations using their specified filter efficiencies, including intake, final, recirculation, new and used; measured airflows, for intake and recirculation; and an assumed intake air leakage of 2 percent, or 0.02, with zero wind infiltration, which was assumed for positive cab pressurization. The recirculation filters used in the current study, whose 0.3–1.0 μm particle collection efficiencies were previously measured in the laboratory, significantly reduced the recirculation airflows of the HVAC system (Organiscak, Cecala and Noll, 2014). These smaller recirculation filters, 7.62 cm (3 in.) high, 40.64 cm (16 in.) wide and 5.08 cm (2 in.) thick, were placed in the recirculation filter location near the floor of the cabs for the additional testing (see Fig. 1).

As illustrated in Fig. 5, the measured PFs were notably lower than the modeled PFs. In order to achieve agreement between them, the intake air leakage into the system would have to be greater than 65 percent, or 0.65. This would appear to be an extreme amount of air leaking around the MERV 16 intake air filter through small cracks or gaps in the HVAC system, and it is more logical to surmise that there were probably additional air leakages around the other filters in the system. Visual inspection of the HVAC system with the filters removed on the roof bolter showed dust deposits downstream of the intake and final filters, indicating multiple leaks in the HVAC system around the filters. A more refined cab filtration system model was formulated by node analysis with these additional leaks (Cecala et al., 2016). This model is represented by the following equation:

$$PF = \frac{C}{x} = \frac{Q_I + Q_R - [Q_R(1 - \eta_R + l_R \eta_R)(1 - \eta_F + l_F \eta_F)] + Q_W}{[Q_I(1 - \eta_I + l_I \eta_I)(1 - \eta_F + l_F \eta_F)] + Q_W}$$

where PF is the cab protection factor; C is the outside contaminant concentration penetrating the filtration system; x is the inside cab contaminant concentration; η is the filter reduction efficiency, fractional; $1 - \eta$ is the filter penetration, fractional; Q is the airflow quantity; I is the air leakage, fractional; and the subscripts F indicate final, I intake, R recirculation and W wind.

The equation provides for a more sensible proportioning of air leakages throughout the filtration system. Face drill air leakages that were modeled bypassing the new intake, recirculation and final filters were 4, 2 and 2 percent, or 0.04, 0.02 and 0.02, respectively, which were doubled for modeling used filters at these locations. Roof bolter air leakages used in the model were further doubled over those used for the face drill, given its significantly lower cab PF field measurements. Additional two- and three-filter system combinations – intake filter with final and/or recirculation filter; MERV 16 and HEPA filters; new and used – were also tested on both of these cabs throughout this long-term study and were modeled using their measured airflow quantities and assumed proportional air leakages described above. For the two-filter systems, zero efficiency was used in the equation for the missing filter, thereby removing its air filtering effect from the model.

Figure 6 shows a comparison of the measured cab PFs and the modeled cab PFs, with reasonable agreement along a unity line. The spread in the data is presumed to be primarily a result of the actual unknown field leakage deviations from the assumed modeled leakages. The figure also shows that the lowest PFs were measured and modeled when no final filter was used. Additionally, the opening points in the figure show there was no observable cab PF benefit to adding the recirculation filter into this system when using the final filter. Adding the recirculation filter into the system significantly reduced the recirculation airflow and cab PF, as illustrated in Fig. 5. A negative aspect of not having the recirculation filter in the system is that dirt and dust from inside the cab would get drawn into and deposited in the HVAC system, thereby increasing maintenance issues. An alternative solution to improving this cab filtration system would be to increase the size of the recirculation filter to increase its airflow capabilities. Finally, leakages in the HVAC/filtration system have a significant impact on cab PFs, as shown when comparing the measured and modeled PFs of the two vehicle cabs. Therefore, the cab HVAC/filtration system needs to be well-sealed to extract the benefits of using high-efficiency dust filters.

Conclusion

A NIOSH comparative study was performed to evaluate the filtering efficiency and air quality inside the enclosed cabs of a roof bolter and a face drill being used at an underground limestone mine when using MERV 16 filters and HEPA filters. The face drill and the roof bolter were each fitted with a filtration system composed of an intake filter and a final filter. The final filter provided a second filtering of the intake air, along with filtering all the air recirculated from within the enclosed cab. The testing showed there was no statistical difference between these two filter types at the 95 percent confidence level for the face drill and the roof bolter. In almost all cases when testing the HEPA filters, the PFs were at their highest when the filters were first installed. As testing progressed and these filters loaded with dust, the PFs, as well as the intake airflows, continually decreased until the

system was not able to provide a sufficient intake airflow and the filters needed to be changed.

In contrast to the HEPA filters, the MERV 16 filters showed improved filtering efficiency over time and use as the filters loaded with dust. Because the MERV 16 filters were less restrictive and provided greater cab pressure, they did not have to be replaced as often as the HEPA filters. This testing also showed the benefits of using a mechanical filtering media, which becomes more efficient with dust loading and the creation of a filter cake. For both the face drill and the roof bolter used in this comparative study, the MERV 16 mechanical filter design was the optimal choice, not only for performance but also for cost. As MERV 16 filters are less expensive than HEPA filters and do not need to be changed as often, which significantly lowers maintenance labor costs, this equates to significant cost savings.

Another key component of this testing was the validation of the substantial improvement in the effectiveness of filtration and pressurization systems when using a final filter design. The final filter adds another level of filtration to remove particulates that leak around the other filters in the HVAC system. However, filters used in the HVAC system should be adequately sized so as not to restrict airflow, thus lowering the system's effectiveness. This was shown not only through the modification expansion of NIOSH's model to include multiple filter applications but also from the actual test matrix performed on the filtration and pressurization systems of the face drill and the roof bolter.

Acknowledgments

We would like to acknowledge Ted DiNardo, mine manager at Shelly Materials, located near Zanesville, OH, and the entire underground limestone mine crew, with special recognition to Jerry Siddle, mine foreman, Jay White, roof-bolter operator, and Harry Montell, face-drill operator. Additionally, we would like to acknowledge Sean Farrell, product engineer, and Ward Morrison, product manager, at Rock & Industrial Mineral Products, with J.H. Fletcher & Co., for their assistance and support of this research effort over a number of years. The cooperation and dedication of all these individuals were instrumental in the success of this study.

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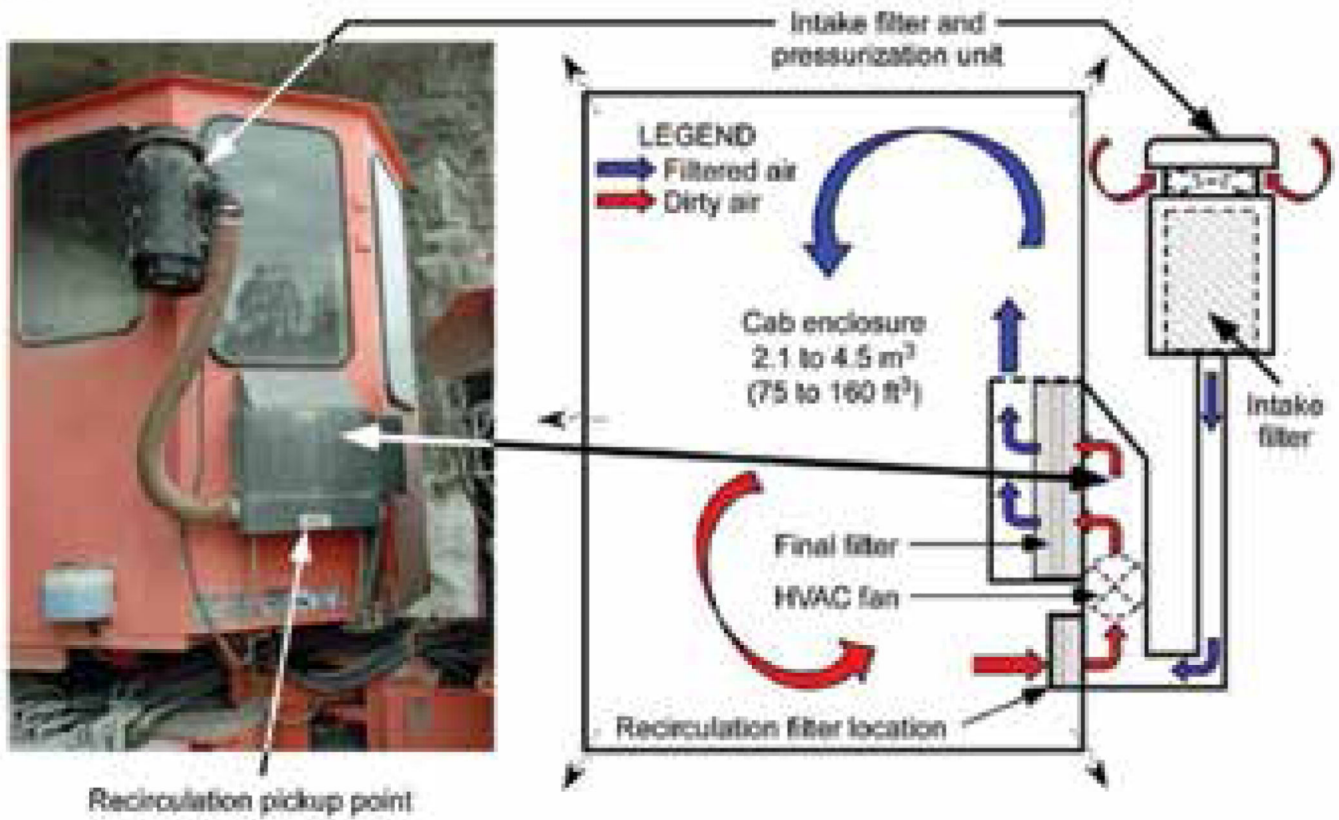
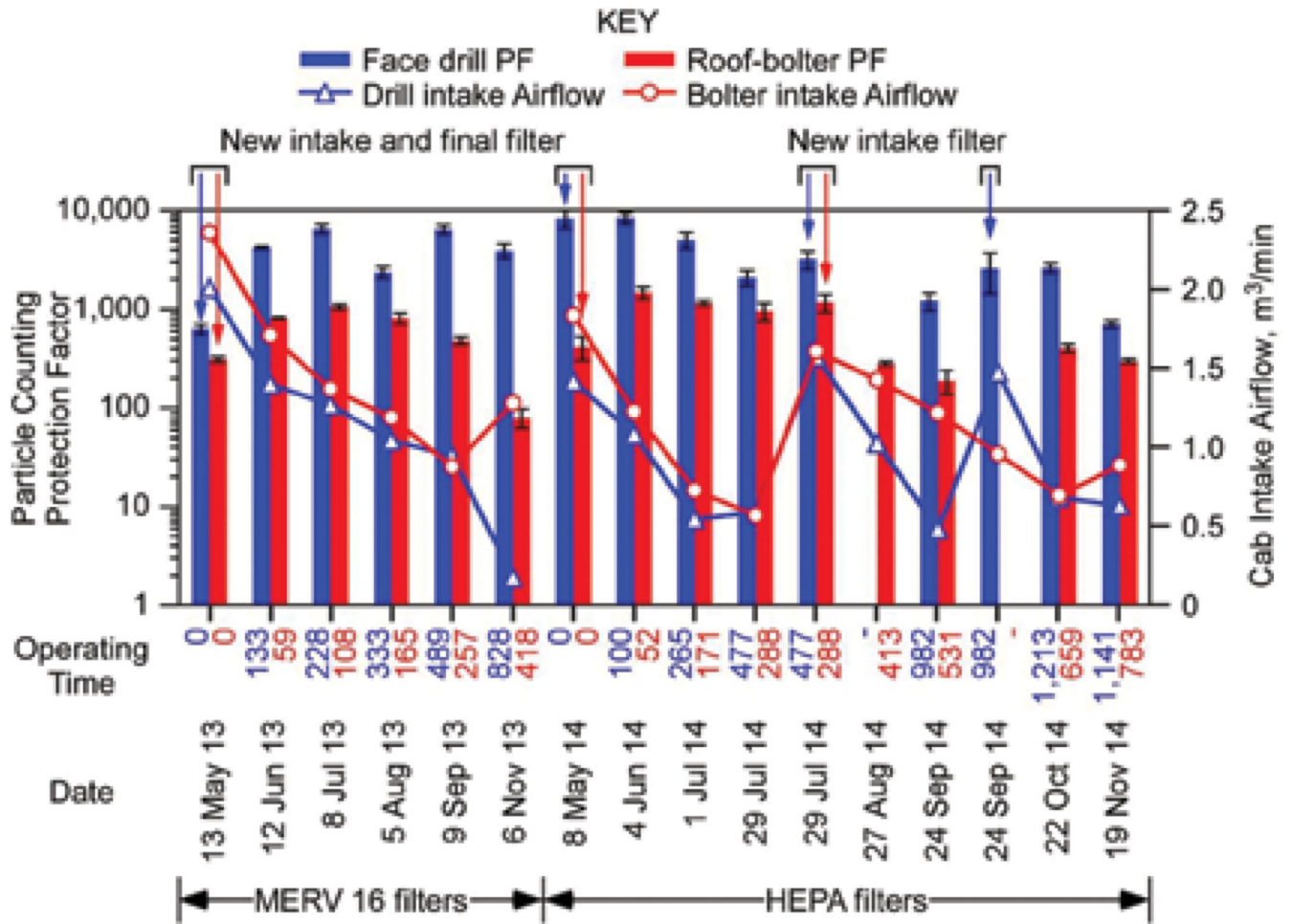


Figure 1. Actual filtration and pressurization unit on an enclosed cab (left) with corresponding plan-view design drawing and airflow pattern (right).



Note: Intake air readings from Nov. 6, 2013 are not shown due to measurement anomalies.

Figure 2. PFs determined from particle countings of the enclosed cabs of the face drill and the roof bolter, and comparison of the intake airflows with the MERV 16 filters and the HEPA filters.

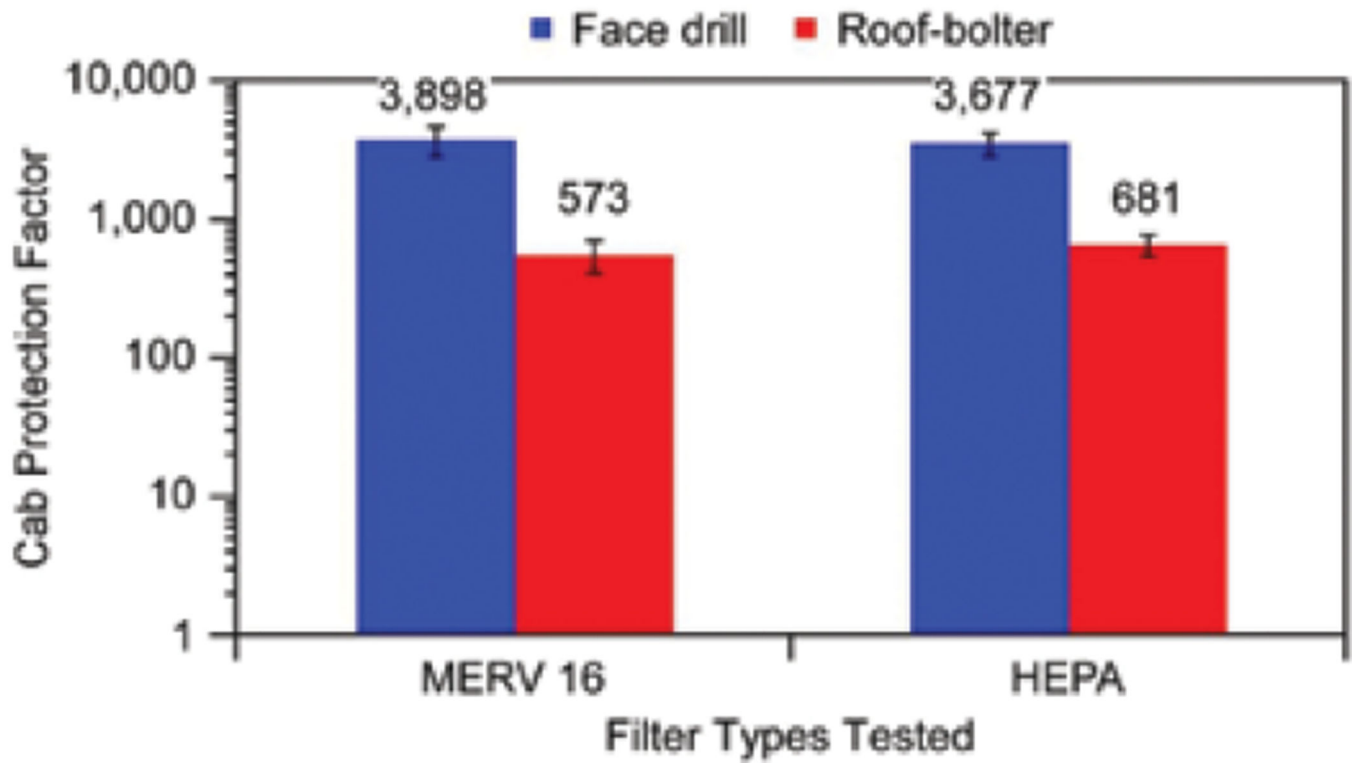


Figure 3. Comparison of the average PF values for the face drill and roof bolter with the MERV 16 filters and the HEPA filters.

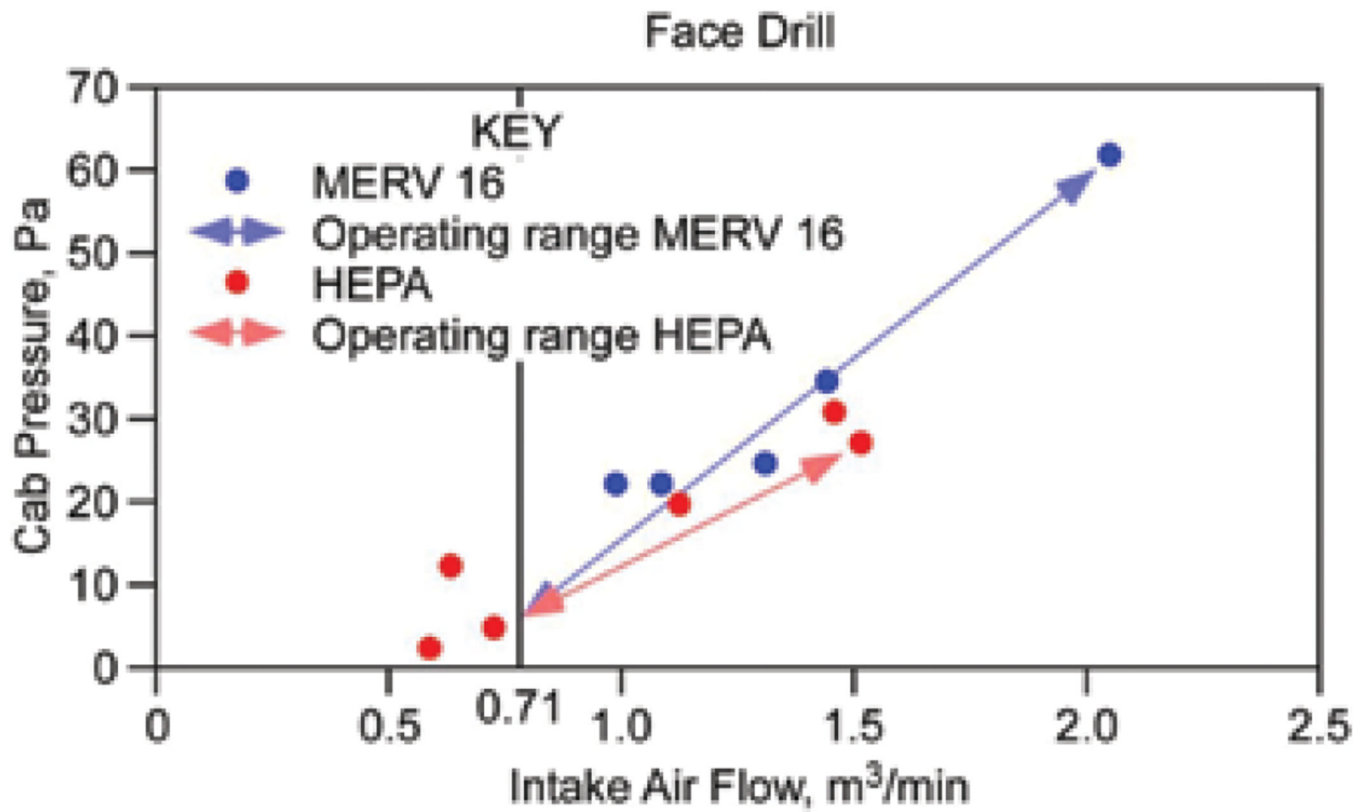


Figure 4. Comparison of the intake airflows and positive cab pressures for the face drill with the MERV 16 filters and the HEPA filters.

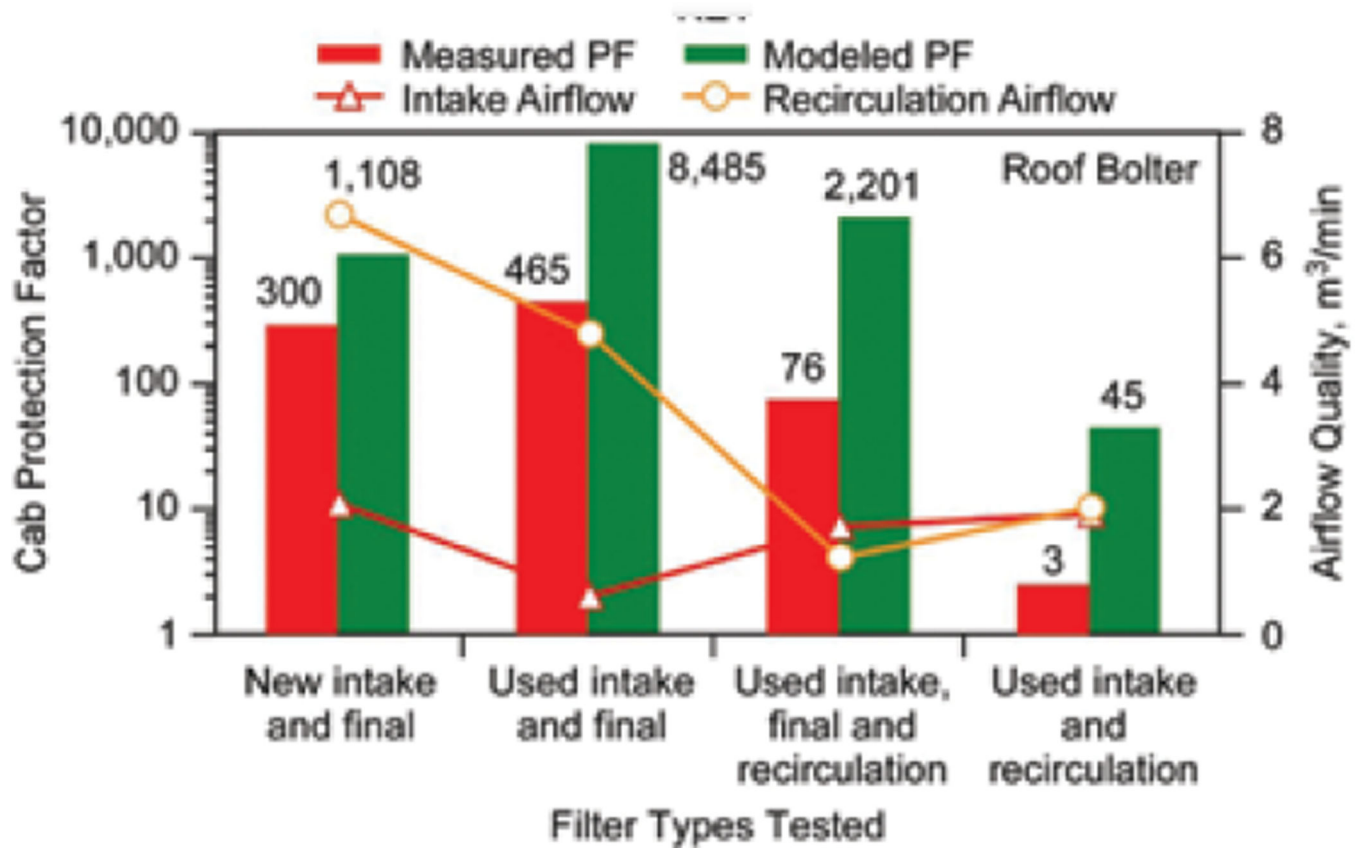


Figure 5. Roof-bolter cab performance changes with respect to different filters used in the system.

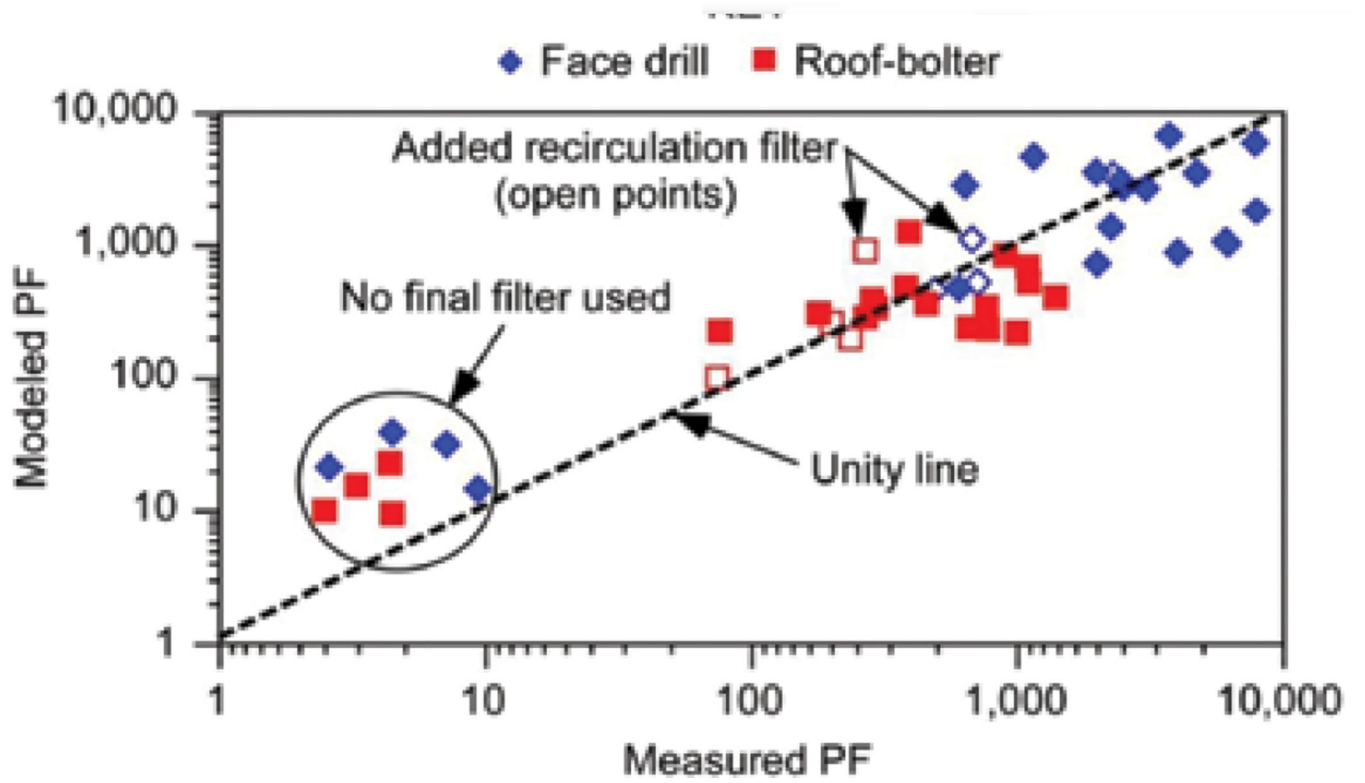


Figure 6. Measured and modeled PFs of the face drill and the roof bolter during the filter field study.

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Table 1

MERV ratings and filtration efficiencies for three size ranges of dust particles (ASHRAE, 2012), and HEPA efficiency.

Group	MERV rating	Average particle size efficiency (PSE)		
		0.3–1.0 μm	1.0–3.0 μm	3.0–10.0 μm
1	1			<20%
	2			<20%
	3			<20%
	4			<20%
2	5			20–34.9%
	6			35–49.9%
	7			50–69.9%
	8			70–84.9%
3	9		<50%	85%
	10		50–64.9%	85%
	11		65–79.9%	85%
	12		80–89.9%	90%
4	13	<75%	90%	90%
	14	75–84.9%	90%	90%
	15	85–94.9%	90%	90%
	16	95%	95%	95%
HEPA		99.97%	99.97%	99.97%

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